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Constraints on Photometric Calibration from Observations of High-Redshift Type Ia Supernovae

David W. Hogg[1,2]
Institute for Advanced Study, Olden Lane, Princeton NJ 08540

ABSTRACT

The good match of the type Ia supernova (SNIa) Hubble Diagram to the prediction of a not-unreasonable cosmological world model shows that measurements of standard stars and their comparison with point sources down to $m = 25$ mag is good to better than ± 0.5 mag over an 11 mag range. It also shows that the true spectral energy distribution (SED) shapes of standard stars are known to better than ± 0.5 mag over an octave in wavelength. On the other hand, the SNIa argument for an accelerating Universe assumes that the magnitude system is good to much better than ~ 0.1 mag over the 11 mag range, and that SED shapes are known to much better than ~ 10 percent over an octave in wavelength. There is no independent empirical evidence for these plausible assumptions.

Subject headings: cosmology: observations — distance scale — standards — stars: fundamental parameters — supernovae: general — techniques: photometric

1. The type Ia supernovae results

The type Ia supernova (SNIa) Hubble Diagrams established by the high-redshift SNIa search and photometry teams (Perlmutter et al 1997; Garnavich et al 1998; Schmidt et al 1998; Riess et al 1998; Perlmutter et al 1999) stand as a great astronomical achievement of this decade. These studies provide a tremendous confirmation of the expanding Universe and big-bang cosmology. Along with massive searches for microlensing events (eg, Alcock et al 1998; Beaulieu et al 1995; Udalski et al 1994), they show that large, coordinated

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[1] Hubble Fellow

[2] hogg@ias.edu

surveys can be established to routinely make discoveries and follow them up uniformly. Along with soon-to-be completed studies of the cosmic background radiation, they hold the promise of making direct, precise measurements of the Universe's kinematics. In fact, at the time of writing, the SNIa results already favor an accelerating Universe, eg, with $(\Omega_M, \Omega_\Lambda) \approx (0.3, 0.7)$ (Riess et al 1998; Perlmutter et al 1999).

One widely overlooked conclusion which can be drawn from the SNIa results is that astronomical photometric calibration systems and techniques are basically correct. In order to make a precise cosmological measurement, the SNIa must span many magnitudes in flux. This requires that it be possible to measure, at the few-percent level, the relative flux between two sources separated by four orders of magnitude. Experiments with this kind of dynamic range are notoriously difficult in any field of study, but particularly in astronomy, where very different instrumentation, techniques, and sources of experimental error become relevant at different magnitude levels. Furthermore, because the SNIa must also span a large redshift interval, different SNIa are observed in different rest-frame bandpasses. This requires that the absolute spectral energy distribution (SED) shapes of the standard stars be known to better than the accuracy of the SNIa measurements (by a factor of at least $\sqrt{N}$).

Given the tremendous care with which our photometric standards have been established and studied, it may not be surprising that the SNIa results are so good. However, it is important to note that the SNIa provide a crucial independent and qualitatively different approach to calibrating photometric measurements. Before the SNIa were established as standard (or standardizable; eg, Riess et al 1996) candles, and before surveys for them spanned the magnitude and redshift ranges they currently span, there were no precise tests of the photometric system by any technique fundamentally different from those by which the system was initially constructed. No astronomical results are secure until they are independently confirmed by qualitatively different techniques.

The subject of this manuscript is the quantitative constraints placed by the SNIa results on photometric calibration.

2. Type Ia supernovae as standard stars

The standard star system currently spans roughly $0 < V < 16$ mag (Johnson & Morgan 1953; Kron et al 1953; Landolt 1973, 1983, 1992). The system is constructed by performing relative observations of groups of stars spanning small overlapping magnitude ranges (typically ~ 5 mag each) at successively fainter magnitudes. The ranges are reconciled with one another to create the $\sim$ 16 mag range currently in use. This has created a "magnitude ladder," with some analogy to the distance ladder, where very faint standards are tied to slightly brighter standards, which are tied in turn to brighter still. It is possible for systematic error to creep in. Of course most of the SNIa are much fainter than the end of the magnitude ladder; there are more opportunities for systematic errors in measuring relative fluxes between the $\sim$ 15 mag standard stars and SNIa as faint as 25 mag.

In principle the standard star ladder could be made irrelevant to the SNIa projects if all SNIa were compared with the same few faint standard stars. In practice, unfortunately, the brightest SNIa were compared with brighter standards, because the fainter standards had not been established. This dependence on brighter standards will become less important when new, bright SNIa are discovered, as long as the new SNIa are compared with the faint standards used with the faint SNIa.

Possible sources for systematic photometry errors, in the standard star system or in the comparison of SNIa with standards, include:

Detector linearity Detector linearity is generally well established for both the photomultiplier tubes employed in calibration and the CCDs employed in SNIa studies, so this is not expected to have a big effect. On the other hand, many CCDs (including the well-studied CCDs in the HST/WFPC2 instrument; Stetson 1998, Whitmore et al 1999) show a "charge transfer efficiency" problem which leads to flux underestimation which itself is a monotonic function of flux. This is exactly the kind of bias which could tilt the flux ladder at the very faint end, although it is only a problem at the few-percent level in HST/WFPC2 and will typically be an even smaller effect in high-background ground-based observations, even with similar instrumentation.

Exposure time differences Generally the SNIa are measured with different exposure times than the standard stars in the SNIa studies (in part to avoid saturation); also bright standard stars are measured with different exposure times than faint ones; it is possible that there are biases in camera shutter controls. This is probably well calibrated for most instruments, at the few-percent level or better. (Also, exposure time changes affect the relative contributions of dark current, read noise, and sky counts in the image; it is not clear that such changes naturally lead to systematic errors.)

Beam switching Standard star calibration measurements which include differencing of on- and off-source counts require that the off-source fields for faint standards be "cleaner" than those for bright standards. In imaging data, such problems are not likely to be bigger than the inverse signal-to-noise ratio (S/N) at which the standards are taken, since that is the level at which nearby faint companions can be observed. This problem therefore ought to be no worse than a few percent per ~ 5 mag range.

Angular correlations of stars Stars are correlated on the sky, and this correlation will no doubt depend on stellar type and magnitude. These correlations could lead to biases in photometric measurements from the very faint stars correlated with their brighter neighboring standard star. Again, this is a problem proportional to the inverse S/N and therefore ought not to be worse than a few percent per ~ 5 mag range. This is not a problem at all if SNIa projects use exactly the same focal-plane aperture as those used in the standard-star calibration programs.

Image combination There can be up to tens-of-percent biases introduced in photometry when multiple images are combined by median filtering or averaging with sigma-clipping (eg, Steidel & Hamilton 1993).

Difference imaging SNIa tend to be observed in time-separated difference images (ie, with and without the SNIa) whereas the standards tend to be observed in on- and off-source difference images. Some sources of noise are very different in these two different kinds of difference, including time variability in the detector and sky for the former, and the numbers and locations of background sources in the latter. Many CCD cameras have few-percent sensitivity variations with temperature and time.

Sky brightness Standard stars tend to be taken at the beginning and end of the night, SNIa during the darkest hours. This changes the relative contributions of dark current, read noise and sky counts to the images. Of course it is not clear that such changes naturally lead to biases. (However, extinction changes which evolve over the night can lead to scatter, if not biases, when the standards are not interleaved into the observing program.)

Bandpasses Filters of the same name on different detectors at different telescopes will be at least slightly different. This can lead to color terms in the photometric systems established with one detector but used to study SNIa with another. The simple fact that the slopes of the sensitivity-wavelength relationships are different at the tens of percent level for different detectors will lead to few-percent differences in broad bandpasses even when identical filters are employed.

Clouds and atmosphere SNIa measurements may be made with less, or at any rate different, attention paid to atmospheric conditions than the standard star calibration measurements. Furthermore, SNIa measurements and standard star calibration have been done at different sites. Even at a fixed site, extinction coefficients for different bandpasses vary with time by factors of a few, and change in color (Landolt 1992). These color changes will affect the shape of the total throughput, telescope plus atmosphere, at the ten-percent level; it will affect relative calibration only at the few-percent level, because standard stars and SNIa are compared through the same bandpass. The magnitude of the problem depends on the differences between the SED shapes of the SNIa and the standards.

Signal-to-noise SNIa, comparison standards, and the stars in the magnitude ladder are all measured at different S/N; some biases depend on S/N alone (Hogg & Turner 1998). These are proportional to inverse S/N; they can only affect the very faintest SNIa at the five to ten-percent level.

It is not clear that any of these possible sources of systematic error will in fact be significant. However, there are enough of them that it is a testament to the care of those who build and calibrate instruments, calibrate the photometric system, and collect and study SNIa that the listed effects do not ruin the SNIa Hubble Diagram.

In fact, the SNIa Hubble Diagram is consistent with a set of cosmological world models within the reasonable range $0 < \Omega_M < 1$ and $0 < \Omega_\Lambda < 1$ (Riess et al 1998; Perlmutter et al 1999). Since this reasonable range spans a magnitude difference of ± 0.5 mag (when tied down to the fluxes of the low-redshift SNIa), the SNIa Hubble Diagram constrains the drift or systematic error in the magnitude system to be less than ± 0.5 mag over 11 mag, or less than 0.045 mag per magnitude.

If the accumulated systematic error is treated as a tilt in the magnitude vs log flux diagram, the SNIa constraint corresponds to the statement that magnitude m is related to flux f by $m = (-2.50 \pm 0.11)\log_{10} f + C$. Constraining systematic error functions more complicated than a linear tilt is difficult with the current sample of known SNIa, which has very few in the redshift range $0.1 < z < 0.4$. This range is crucial for investigating the magnitude-dependence of any systematic errors, since it spans a large range in magnitude but is not strongly affected by changes in the world model.

It is possible to remove the world model uncertainty by just considering the ~ 6 mag range of $z < 0.1$ SNIa observations whose interpretation is relatively independent of cosmological world model. Although the interpretation of these SNIa has less dependence on world model, the constraint on the photometric system is weaker, because the magnitude baseline is shorter.

A similar constraint on the magnitude system can be derived from photometry of Cepheids in the water-maser galaxy NGC 4258 (Maoz et al 1999), where the absolute distance is known from the kinematics of the water masers near the nucleus of the galaxy (Hernstein et al 1999). The comparison with the Large Magellanic Cloud spans 11 mag, and the uncertainty, including both the NGC 4258 and LMC distance uncertainties, is on the order of 0.3 mag.

Taken at face value, the SNIa results currently favor an accelerating Universe with $\Omega_\Lambda > 0$. In the SNIa Hubble Diagram, these world models are separated from non-accelerating world models with $\Omega_\Lambda = 0$ by only ≈ 0.1 mag. (At fixed Ω_M, accelerating and non-accelerating world models are separated by more than 0.1 mag. However, the closest non-accelerating world model to any non-accelerating one is as close as ≈ 0.1 mag.) Until there is independent empirical evidence that relative photometry techniques are linear to much better than 0.1 mag over that 11 mag range, the SNIa will not particularly favor accelerating ($\Omega_\Lambda > 0$) world models over non-accelerating ($\Omega_\Lambda = 0$) ones.

3. Type Ia supernovae as SED-shape calibrators

Observations of SNIa currently span much of the redshift range $0 < z < 1$, so observations in a particular wavelength bandpass span a range of emitted wavelengths. For this reason, even if the underlying SED shapes of SNIa are unknown, the mere fact that they are standard (or standardizable) candles implies that they can be used to calibrate the relative sensitivities of different bandpasses.

Usually observations are carried out all in a particular, fixed set of observational bandpasses, so the magnitudes must be k-corrected. The k-correction is the difference between the observed magnitude of a redshifted source and the magnitude which would have been observed for the source at the same distance but zero redshift. It depends on the individual SED shape of the source being observed because it is a logarithmic ratio of absolute fluxes in different bandpasses (observed and emitted). Here, clearly the k-correction is as good as our knowledge of the SED shape of the source. Although the source can be compared very accurately to standard stars such as Vega, the SED shape can only be known as well as the SED shapes of the standard stars.

In principle a SNIa project could be designed such that sources at different redshifts are observed in different bandpasses, matched so that the observed fluxes of the SNe are observed at the same emitted wavelengths at all redshifts. This technique is also dependent on the SED shapes of the standard stars, because SNIa at different redshifts will have to be calibrated against different parts of the standard stars' SEDs.

The SED shapes of Vega and other standard stars are measured by comparison with laboratory blackbodies of known temperatures. The blackbody is close to the telescope (relative to the standard stars!), so airmass corrections have to be extrapolated from zero airmass to the airmasses of the stellar observations (Hayes 1970; Oke & Schild 1970). An alternative method of absolute calibration makes use of synthetic photometry of model stellar atmospheres (eg, Colina & Bohlin, 1994).

Possible sources for systematic errors in standard star SEDs include:

Laboratory blackbody temperatures The inferred SED shapes are really relative to the laboratory blackbody SED shape, so errors in temperature lead to SED shape errors. However, the laboratory blackbodies are very precise, so there is unlikely to be much temperature uncertainty; certainly $\Delta T/T < 10^{-3}$ (Hayes 1970; Oke & Schild 1970).

Illumination geometry The blackbodies are point sources near the telescope, calibrated in luminosity, whereas stars are point sources at infinity and are being calibrated in flux. The two will not illuminate the telescope and its instrumentation identically. The experiments are done carefully, so this error is not likely to be bigger than the angle the telescope aperture subtends to the blackbody, or on the order of a few percent.

Absorption layers in the atmosphere The extrapolation of the blackbody observations from zero to finite airmass depends on an extrapolation of airmass corrections from observations at airmasses of, say, 1 to 2 down to zero. This extrapolation is not trivial if there are non-uniform absorbing layers in the atmosphere, or if the absorption at some wavelengths happens mainly at low altitude. The extrapolation has been tested at the ten-percent level (Stebbins & Kron 1964).

Deviations of bandpass shapes The SNIa and standard stars are compared in finite bandpasses, not through spectrophotometry. If any aspect of bandpass estimation (telescope optics transmission, detector efficiency, filter curve) is uncertain, an uncertainty is introduced into the locations and widths of the bandpasses in wavelength space. This problem is not likely to be big for the SNIa projects, which have gone to great pains to assess their photometric systems (eg, Kim et al 1996).

Atmospheric extinction variations Extinction coefficients for different bandpasses vary with time by factors of a few, and change in color, even at a fixed telescope site (Landolt 1992). These color changes will affect the shape of the total throughput, telescope plus atmosphere, at the ten-percent level; it will affect SED-shape inference at the few-percent level.

Incorrect model spectra In the case of synthetic photometric calibration, the accuracy of the result is directly related to the accuracy of the model spectra. This is hard to assess, since the only calibration-independent tests of model spectra are the equivalent widths of lines and fractional strengths of spectral breaks, while it is the absolute level of the continuum that is involved in the calibration. However, there are some astronomical sources which are thought to be very accurately modeled astrophysically. Synthetic and blackbody calibrations may disagree at the five-percent level (eg, Colina & Bohlin, 1994).

Again, it is not clear that any of these possible sources of systematic error is significant, but it is nonetheless impressive that these effects do not ruin the SNIa Hubble Diagram.

The fact that the SNIa Hubble Diagram is consistent with a set of cosmological world models within the reasonable range $0 < \Omega_M < 1$ and $0 < \Omega_\Lambda < 1$ constrains the SED error to be less than ± 0.5 mag over the wavelength range spanned by the redshift range $0 < z < 1$, ie, over a factor of two in wavelength. If SED shapes could be off by a significant fraction of 10 percent over the factor of two in wavelength, then the SNIa do not particularly favor accelerating world models over non-accelerating ones.

4. Conclusions

The reasonableness of the SNIa results show that relative photometric calibration is good to within ± 0.5 mag over ~ 11 mag and that the SED shapes of standard stars are known to ± 0.5 mag over a factor of two in wavelength. Although perhaps these constraints are not surprising, they testify to the quality of the photometric calibration, both of the standard star system, and of the SNIa projects. These constraints are important because they are completely independent of the astronomical techniques used to construct the calibration in the first place. If the calibration is uncertain at the few to ten-percent level over the same magnitude or wavelength range, then there is no more SNIa evidence for an accelerating Universe.

Standard candles provide an invaluable resource for testing or, perhaps, in the future, even establishing systems of calibration. Unfortunately, they are rare. However, it is conceivable that certain kinds of calibration verification similar to that described here could be performed with massive, uniform sky surveys such as the Sloan Digital Sky Survey (SDSS). Because the SDSS collects uniform data on a huge range of galaxies over a range of redshifts, it will be possible to constrain certain aspects of photometric calibration. For example, if the r-band absolute calibration was low by ten percent, then all populations of extragalactic objects would appear to brighten at rest-frame 7000 Å in going from redshift $z = 0.4$ to $z = 0.0$ but fade at rest-frame 5000 Å over the same redshift interval. Intercomparison of the evolutionary behaviors of different extragalactic populations may therefore constrain many aspects of calibration. Like SNIa constraints on calibration, these would also be independent of the standard star system. This future project stands as possibly the least glamorous goal of the SDSS.

Unfortunately, the prospects for finding new alternatives for independent verification of photometric calibration are not good. The main approach to improving relative photometry is, and should be, increased testing of detector and instrument linearity and repeatability, and continued calibration of standards at fainter levels and higher signal-to-noise ratio. Some tests of telescope linearity could involve "stopping down" a large telescope, perhaps with a randomly perforated entrance cover (since any neutral-density filter is as hard to calibrate as the photometry itself!). A stopped-down telescope would permit some differential tests of photometry that remove many (though not all) of the aforementioned systematic problems. A radical idea, fraught with a new set of observational difficulties, is to observe, at aphelion and perihelion, asteroids on highly elliptical orbits around the Sun (B. Paczynski. private communication).

As for constraining cosmological world models, the SNIa projects will become much less sensitive to photometric calibration as they push to higher redshifts, where differing world models make very different predictions, which are themselves different from the expected flux-dependence of most of the possible systematic errors.

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REFERENCES

Alcock C. et al 1998, ApJ 492 190

Beaulieu J. P. et al 1995, A&A 299 168

Colina L., Bohlin R. C., 1994, AJ 108 1931

Cousins A. W. J., 1976, Mon. Not. Astron. Soc. S. Afr. 35 70

Garnavich P. M. et al, 1998, ApJ 493 53

Hayes D. S., 1970, ApJ 159 165

Herrnstein J. R., et al, 1999, Nature 400 539

Hogg D. W., Turner E. L., 1998, PASP 110 727

Johnson H. L., Morgan W. W., 1953, ApJ 117 313

Kim A., Goobar A., Perlmutter S., 1996, PASP 108 190

Kron G. E., White H. S., Gascoigne S. C. B., 1953, ApJ 118 502

Landolt A. U., 1973, AJ 78 959

Landolt A. U., 1983, AJ 88 439

Landolt A. U., 1992, AJ 104 340

Maoz E., Newman J. A., Ferrarese L., Stetson P. B., Zepf S. E., Davis M., Freedman W. L., Madore B. F. 1999, Nature 401 351

Oke J. B., Schild R. E., 1970, ApJ 161 1015

Perlmutter S. et al, 1997, ApJ 483 565

Perlmutter S. et al, 1999, ApJ 517 565

Riess A. G., Press W. H., Kirshner R. P., 1996, ApJ 473 88

Riess A. G. et al. 1998, AJ, 116, 1009

Schmidt B. P. et al, 1998, ApJ 507 46

Stebbins J. & Kron G. E., 1964, ApJ 139 424

Steidel C. C., Hamilton D., 1993, AJ 105 2017

Stetson P. B., 1998, PASP 110 1448

Udalski A. et al, 1994, Acta Astron. 44 165

Whitmore B., Heyer I., Casertano S., 1999, PASP 111 1559